Combination Test/Analysis Method Used To Demonstrate Compliance To DOE Type B Packaging Thermal Test Requirements

(30 Minute Fire Test)

Defense Programs Guideline for Weapon Component Packaging

[SG 140.1]

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1. Scope

Applicants requesting certification of packaging for transport of Defense Programs radioactive material under DOE Order 5610.1 must, in general, show that the packaging conforms to the DOE performance requirements adopted from 10 CFR 71. The subject of this paper is the DOE interpretation of the hypothetical accident scenario described in 10 CFR 71.73 (c), (3) as follows:

> "(3) Thermal. Exposure of the whole specimen for not less than 30 minutes to a heat flux not less than that of a radiation environment of 800 °C (1475 °F) with an emissivity coefficient of at least 0.9. For purposes of calculation, the surface absorptivity must be either that value which the package may be expected to possess if exposed to a fire or 0.8, whichever is greater. In addition, when significant, convective heat input must be included on the basis of still, ambient air at 800 °C (1475 °F). Artificial cooling must not be applied after cessation of external heat input and any combustion of materials of construction must be allowed to proceed until it terminates naturally. The effects of solar radiation may be neglected prior to, during, and following the test."

This paper has been prepared as a guideline to ensure that applicants are aware of DOE's interpretation of the requirement and to provide consistent review policy. It should be recognized by both DOE regulatory certifying personnel and applicants using this guideline that other viable means of demonstrating conformance may exist and that it is not the intent of this guideline to imply that any such methods may or may not be acceptable. Specifically, this guideline is applicable to a combination test/analysis methodology which involves heating a package in a furnace or other enclosed radiative environment where the package and the furnace have similar geometric shapes or where dimensional considerations allow the assumption of similar geometric shape.

2. Introduction

2.1 Radiation Heat Transfer

Consider a package inside a furnace where the package is at an absolute temperature T_P and the furnace is at an absolute temperature T_F and $T_F > T_P$. It may be shown that the heat transfer, q, due to the net radiation exchange between the furnace and the package is given by Equation 1 [1]:

$$q_{F-P} = q_{P-F} = A_F F_{F-P} \sigma T_F^4 - A_P F_{P-F} \sigma T_P^4 \tag{1}$$

where:

A_F = the surface area of the furnace (m^2)
A_P = the surface area of the package (m^2)
σ = the Stefan-Boltzmann constant ($W/m^2 {}^\circ K^4$)
F_{F-P} = the interchange factor between the furnace and the package
F_{P-F} = the interchange factor between the package and the furnace

It becomes apparent that when the system reaches steady state, $q_{F-P} = q_{P-F} = 0$, and that $T_P = T_F$ so that:

$$A_F F_{F-P} = A_P F_{P-F} \tag{2}$$

Therefore, the two expressions are equivalent and can be used interchangeably. Equation 2 is also valid for the transient condition, i. e., $T_P \neq T_F$ [1]. Equation 2 can be substituted into Equation 1 to give an expression for the radiative heat transfer from the furnace to the package.

$$q_{F-P} = A_F F_{F-P} \sigma \left(T_F^4 - T_P^4\right) \tag{3}$$

The total interchange area between the furnace and the package, $A_F F_{F-P}$, can be evaluated for a typical package inside a furnace by using an expression developed by Hottel [1].

$$A_F F_{F-P} = \frac{1}{\left(\dfrac{1-\epsilon_P}{\epsilon_P A_P}\right) + \left(\dfrac{1}{A_P \overline{F}_{P-F}}\right) + \left(\dfrac{1-\epsilon_F}{\epsilon_F A_F}\right)} \tag{4}$$

The derivation of Equation 4 assumes that both the package and the furnace are isothermal "gray" bodies for which the emissivity, ϵ, is equal to the absorptivity, α, and is independent of the spectral energy distribution of the incident radiation. When the package is inside the furnace and is constructed in such a manner that the package does not "see" itself, the view factor F_{P-F} equals 1. Equation 4 can be rewritten,

$$A_F F_{F-P} = \frac{A_P}{\left(\dfrac{1}{\epsilon_P}\right) + \dfrac{A_P}{A_F}\left(\dfrac{1-\epsilon_F}{\epsilon_F}\right)} \tag{5}$$

substituted into Equation 3 and rearranged to give the expression for the heat flux from the furnace to the package.

$$\frac{q_{F-P}}{A_P} = \frac{\sigma \left(T_F^4 - T_P^4\right)}{\left(\dfrac{1}{\epsilon_P}\right) + \dfrac{A_P}{A_F}\left(\dfrac{1-\epsilon_F}{\epsilon_F}\right)} \tag{6}$$

Equation 6 is the general equation to be used to evaluate the heat flux from the furnace to the package. The assumptions used to develop Equation 6 are repeated below:

(1) The package and the furnace have similar shapes or may be assumed to have similar shapes.
(2) The package view factor is equal to 1.
(3) The furnace and the package are isothermal "gray" bodies.

The analysis method demonstrated develops an expression for the specified radiative heat flux based on classical radiation heat transfer theory and DOE's interpretation after which the expression is equated to the actual heat flux received by the package during the test. Examples using this method are given in Appendix A.

2.2 The Specified Radiative Heat Flux

The furnace to package radiative heat flux specifies a furnace emissivity, ϵ, of 0.9 and a minimum furnace wall temperature of 800 °C. The package absorptivity, α, which is equal to the package emissivity, ϵ, from the gray body assumption, is taken to be 0.8 minimum, to account for soot buildup on the package surface as a result of the hypothetical fire. The package to furnace area ratio is not specified however it is clear that the intent of the regulation is to simulate a fire. An all encompassing fire would, under ideal conditions, equate to a package to furnace area ratio of 1 [2]. It should be noted that the subsequent analysis can show that the value of 1 is the least conservative value. Applicants are encouraged to be more conservative in their choice of an area ratio value. The remaining variable is the initial package temperature, T_P. The initial package temperature, T_P, will be the actual package temperature at the start of the 30 minute test. The specified radiative heat flux to the package may now be written as:

$$\left(\frac{q_{F-P}}{A_P}\right)_{Reg} = \frac{\sigma\,(T_F^4 - T_P^4)}{\left(\frac{1}{\epsilon_P}\right) + \frac{A_F}{A_P}\left(\frac{1-\epsilon_F}{\epsilon_F}\right)} = \frac{\sigma\,(1075^4 - T_P^4)}{\left(\frac{1}{\epsilon_P}\right) + 1\left(\frac{1-0.9}{0.9}\right)} \qquad (7)$$

where ϵ_P is 0.8 minimum and T_P (°K) is as previously discussed. The subscript "Reg" is added for clarity to indicate a specified value.

2.2.1 Steady-state Method of Compliance

Referring to Equation 7, it is evident that when T_P is 1075 °K (800 °C), the heat flux is zero. This provides another means of demonstrating compliance. Specifically, if the package surface is uniformly held at a temperature greater than or equal to 800 °C for no less than 30 minutes, the requirement has been met. The furnace wall temperature must remain at 800 °C, minimum, throughout the test.

2.3 The Actual Radiative Heat Flux

2.3.1 Furnaces Utilizing a Non-participating Medium

For furnaces utilizing a non-participating medium, i.e., electrically-heated furnaces, the actual radiative heat flux from the furnace to the package can be written as:

$$\left(\frac{q_{F-P}}{A_P}\right)_{Act} = \frac{\sigma\,(T_{F*}^4 - T_P^4)}{\left(\frac{1}{\epsilon_P}\right)_{Act} + \left(\frac{A_P}{A_F}\left(\frac{1-\epsilon_F}{\epsilon_F}\right)\right)_{Act}} \tag{8}$$

where the subscript "Act" refers to the actual properties of the furnace and the package and the package temperature, T_P, is the actual package temperature at the start of the 30 minute test period as previously discussed. For most packages used in Defense Programs, i.e., carbon or stainless steel drums providing the outer shell, the package surface emissivity increases with increasing temperature. For these cases the applicant may use a package emissivity corresponding to T_P, or, if sufficient data is provided, the package emissivity used may reflect the temperature range between T_P and $T \leq T_{F*}$. Applicants are encouraged to be conservative and evaluate the package emissivity at T_P. The furnace temperature, T_{F*}, is the minimum absolute temperature, at the furnace wall, required for the actual test ($\geq$ 800 °C). The furnace emissivity may also increase with increasing temperature however the furnace emissivity used shall be the emissivity value at 800 °C (1475 °F), maximum. In any case, the applicant will be required to justify all values used in Equation 8. Applicants will also be required to provide justification, i. e., measurements, etc., for the effects of any package coatings or surface treatments on the package emissivity as a function of temperature.

2.3.2 Furnaces Utilizing a Participating Medium

For furnaces utilizing a participating medium, i.e., most gas-fired furnaces in which the furnace gas is hotter than the furnace walls, the heat flux to the package is also dependent upon the emissivity and temperature of the furnace gas [3]. The radiative heat flux from the furnace to the package can be written as:

$$\frac{q_{F-P}}{A_P} = \frac{\sigma\left[\left(\epsilon_P\left[\frac{\epsilon_g + \epsilon_F - \epsilon_g\epsilon_F}{\epsilon_g(1-\epsilon_g)\,\epsilon_F} + \frac{A_P(1-\epsilon_F)}{A_F\epsilon_F}\right](T_g^4 - T_P^4)\right) - \frac{\epsilon_P}{\epsilon_g}(T_g^4 - T_F{*}^4)\right]}{\frac{\epsilon_g + \epsilon_F - \epsilon_g\epsilon_F}{\epsilon_g(1-\epsilon_g)\,\epsilon_F}\left[1 + \left(\frac{A_P}{A_F}(1-\epsilon_g)(1-\epsilon_F)\left[\frac{\epsilon_g + \epsilon_P - \epsilon_g\epsilon_P}{\epsilon_g + \epsilon_F - \epsilon_g\epsilon_F}\right]\right)\right]} \tag{9}$$

where: ϵ_g = the emissivity of the furnace gas
T_g = the furnace gas temperature (°K)

and the remaining variables represent actual properties or values as previously defined. The furnace thermocouples used to measure T_g, T_F, and T_P are affected by contributions from the gas and furnace wall temperatures, i.e., the measured temperatures are between the temperature of the furnace gas and the average temperature between the furnace walls and the test package [4]. Therefore, given the types of furnaces readily available for testing DP packagings, use of Equation 9 requires considerable furnace characterization prior to testing. Assuming adequate furnace characterization, the use of Equation 9 gives credit for the additional contribution of the furnace gas to the heat flux received by the package and results in a lower furnace wall temperature, T_{F*}, when compared to the use of Equation 8.

2.4 Analysis Method

The analysis method is straightforward and consists of the following steps:

(1) The package emissivity, ϵ_P, used in Equation 7 is 0.8, minimum.
(2) Determine T_P for use in Equation 7.
(3) Calculate ϵ_F at 800 °C (1475 °F), maximum, for use in Equation 8 or Equation 9, as applicable.
(4) Calculate $\epsilon_P = f(T_P)$ or $\epsilon_P = f(T_P, T \leq T_{F*})$ for use in Equation 8 or Equation 9, as applicable.
(5) The value of T_P determined in step 2 is used in Equation 8 or Equation 9, as applicable.
(6) Set the right hand side of Equations 7 and 8 (or Equation 9) equal to one another and solve for T_{F*}.

The calculated effective furnace wall temperature, T_{F*}, is the minimum value that must be used to demonstrate compliance. A furnace wall may include heating and wall elements that are at different temperatures. When the method is being used to verify a previous test, the calculated T_{F*} must be less than or equal to the lowest furnace wall temperature value used in the test. For a proposed test, T_{F*} yields the minimum furnace wall temperature required. In either case, T_{F*} may never be less than 800 °C (1475 °F).

2.4.1 Packaging Support Structures Used in Furnace Tests

It is recognized that during the actual test(s) some type of support structure may be needed to safely support the package prior to, during, and after the time it is in the furnace. Supports should be designed so as not to significantly inhibit heat transfer to the package. Such supports need not be considered in the analysis, however the regulator, usually the review panel chairperson or his designated appointee, reserves the right to make the final determination based on a review and/or inspection of each case.

2.5 Effects of Convection

The heat transfer contribution due to convection will vary depending upon the package and furnace geometries, package orientation, the type of furnace used for each test, and the relative volume of the furnace to the package. Some electrically heated furnaces may have only a relatively small convection effect while certain furnaces that utilize an actual flame for the heat source may have significant convection effects. Actual testing results in convective effects being imposed upon the package. It remains the responsibility of the applicant to define the convection conditions and justify all comments and analysis regarding convection.

3. Duration of Test

After calculating the required minimum effective furnace wall temperature, T_{F*}, and the actual package emissivity, ϵ_P, the test plan must ensure that: (1) an adequate amount of time is allotted for the furnace to stabilize, i. e., $T \geq T_{F*}$, both before and after the package is put into the furnace, and (2) the initial package temperature, T_P, corresponds to the value of actual package emissivity, ϵ_P, that was used to determine T_{F*} in the calculations. The minimum test duration is 30 minutes after the furnace has stabilized and the package is at a temperature no less than T_P.

4. Summary

(1) When calculating the specified initial heat flux, applicants: (a) May use a package to furnace surface area ratio of 1. Smaller values are suggested but not required. (b) Must use a package emissivity of 0.8 minimum and a furnace surface emissivity of 0.9. (c) Must use a furnace wall temperature of 1075 °K (1935 °R). Applicants must present, discuss, and show sufficient justification for the values used in (a), (b), and (c) above.

(2) When calculating the actual initial heat flux received by the package during the test, applicants: (a) Must use the actual package to furnace surface area ratio. (b) Must use the actual furnace emissivity at 800 °C (1475 °F). (c) Must use the actual package emissivity. Package emissivity used is either evaluated at the package temperature at the start of the test or as a function of the temperature range experienced by the package. Applicants must present, discuss, and show sufficient justification for the values used in (a), (b), and (c) above.

(3) The calculated furnace temperature (T_{F*}) is the minimum furnace wall temperature that can be used in a test.

(4) Support structures used prior to, during, and after testing must be designed so as not to inhibit heat transfer to the package. In cases of review panel disagreement the review panel chairperson will make the determination.

(5) Although convection may be neglected in many cases, it is the responsibility of the applicant to present and discuss the effects, or lack thereof, of convection to the package.

(6) The furnace atmosphere must be oxidizing so as not to prevent oxidation or combustion of package materials.

REFERENCES

[1] McAdams, Heat Transmission, 3rd edition, Chapter IV by H. C. Hottel, McGraw-Hill, New York(1954).

[2] W. H. Lake, U.S. Nuclear Regulatory Commission, THERMAL ANALYSIS OF PACKAGING USING THE INTEGRAL METHOD, PATRAM '83, 7th International Symposium on Packaging and Transportation of Radioactive Materials, page 1079, Transportation Technology Center, Sandia National Laboratories and Oak Ridge National Laboratory, New Orleans, Louisiana, (May 15-20, 1983).

[3] V. Babrauskas and R. B. Williamson, Temperature Measurement in Fire Test Furnaces, Fire Technology, **14**, 226-238, (1978).

[4] N. R. Keltner and J. L. Moya, Defining the Thermal Environment in Fire Tests, Fire and Materials, Volume 14, 133-138, (1989).

APPENDIX A

A.1 This Appendix will present and discuss examples that use the method discussed in this guideline. The examples assume that all assumptions and values have been sufficiently presented, discussed, and justified in the application for packaging certification.

Example 1 Calculating the Correct Furnace Wall Temperature.

Specified data:

Package emissivity of 0.8, package temperature at the start of the test period is 121 °C (396 °K), area ratio of 1, non-participating medium.

Actual furnace and package data:

Package to furnace surface area ratio of 0.08, package emissivity of 0.65 at 396 °K, package starting temperature of 396 °K, furnace emissivity of 0.59 evaluated at 800 °C (1475 °F), no significant convection effects, support structure not a factor.

Calculation:

Using the above values in Equations 7 and 8, as appropriate, gives a furnace wall temperature, T_{F^*}*, of 844 °C.*

Additional details:

The furnace was set so that the minimum wall temperature would be 844 °C. The door was opened and the package was put in the furnace. It took 3.5 minutes for the furnace to stabilize back to 844 °C after which an additional 5 minutes was required for the package surface temperature to reach 121 °C. The 30 minute test period started 9 minutes after the package was put in the oven.

Example 2 Calculating the Correct Furnace Wall Temperature.

This example is identical to Example 1, except the furnace utilizes a participating medium. The temperature of the furnace gas, T_g*, is measured and found to be 1175 °K. The corresponding gas emissivity,* ϵ_g*, is 0.1.*

Calculation:

Using the appropriate values in Equations 7 and 9 results in a furnace wall temperature, T_{F^*}*, of 828 °C.*

> ***[Note that the contribution to the heat flux from the gas flame results in a furnace wall temperature that is 16 °C lower than in the previous example.]***